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SYNTHESIS OF PLANAR MECHANISMS, PART XI: AL-JAZARI QUICK RETURN-MOTION MECHANISM

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Abstract:-
This is the 11th research papers in a series of papers aiming at the optimal synthesis of planar mechanisms. The mechanism in hand is invented by Al-Jazari in the 12/13th century and is analyzed before by the author for a specific time ration, stroke and transmission angle. In the present work the mechanism is optimally synthesized for maximum time ratio and desired normalized stroke. Five functional constraints are defined to control the performance of the mechanism. The MATLAB optimization toolbox is used and four dimensions of the mechanism are assigned in a normalized form. Normalized stroke range from 1 to 5.45 is covered and the study shows that it is possible with Al-Jazari mechanism configuration to go to a time ratio as large as 6.3. The optimized synthesis of the mechanism can keep the transmission angle of the mechanism during complete crank rotation within a range from 45 to 116.7 degrees for the range covered for the desired normalized stroke.

Keywords: - *Al-Jazari quick return motion mechanism, optimal mechanism synthesis, maximum time ratio.*

I. INTRODUCTION

Al-Jazari quick return motion mechanism is one of the mechanisms used in operating positive displacement pumps. This mechanism is capable of providing relatively large normalized stroke and large time ratio up to 6. The optimal synthesis of the mechanism is presented in the present work with the purpose of maximizing the mechanism time ratio and keeping good performance of the mechanism.

C. Xian (2005) studied a kinematic synthesis approach for planar 4, 5 and 6 bar mechanisms. He presented the mathematical model and algorithm for planar inverted crank-slider mechanism, 2DOF 5 bar hybrid driven linkages and Watt and Stephenson type 6 bar linkages [1]. Dong and Wang (2007) studied the optimization synthesis of 6 bar dwell mechanisms. They established a unified mathematical model based on the adaptive curve fitting approach and verified the efficiency and accuracy of their approach [2]. Pennock and Israr (2009) investigated the dynamics of an adjustable 6-bar linkage in which the output link had an angular oscillating motion. They examined the extreme positions of the output link corresponding to the extreme positions of point on the coupler [3]. Liu and Chou (2011) proposed an intelligent evolutionalry algorithm which employed a multimodal 6 bar mechanism optimization design. They showed how their developed technique was effective at resolving optimal automatic system design problems [4].

Sedano et. al. (2012) presented a hybrid optimization approach for the design of linkages. They applied their method to the dimensional synthesis of mechanism and combined the merits of stochastic and deterministic optimization. They tested the efficiency, robustness and accuracy of their proposed method using two examples [5]. Wang (2013) established kinematics mode of the 6 bar drawing mechanism by bar group method. The optimal results showed that the performance of kinematics had improved greatly [6]. Kanakaraddi, Kulkarni and Konnur (2014) generated a desired function by adjusting the coupler length of a six bar mechanism. They developed a procedure to compute the precision points using Chebychev spacing and utilizing them in obtaining the dimensions of the desired mechanism from Fruedenstein's method [7].

Hassaan (2014) formulated the optimal synthesis problem of a single dwell 6-bar planar linkage. He used the transmission angle at two locations to control the performance of the synthesized mechanism. He could produce a dwell within 60 degrees of crank rotation with a maximum error less than 0.23 % [8]. Soh and Ying (2015) formulated a systematic design methodology for the design of planar six and eight bar slider mechanisms for motion generation applications requiring more complex motion than the slider-crank mechanism [9]. Hassaan (2015) presented an approach for the synthesis of three planar mechanisms including Al-Jazari quick return motion mechanism. He used a synthesis conditions of specific stroke, time ratio and transmission angle. He used MATLAB in solving the kinematic nonlinear equations of each mechanism [10]. Hassaan (2015) investigated the synthesis of a 6 bar – 3 sliders mechanism for motion generation having maximum time ratio and an assigned normalized stroke. He covered a desired normalized stroke from three to eight and the maximum time ratio obtained was up to 3 [11].

II. THE MECHANISM

The quick return motion mechanism of Al-Jazari was used by his inventor to drive a 2 cylinders positive displacement pump driven automatically by an undershot water wheel as shown in Fig.1 [12], [13].

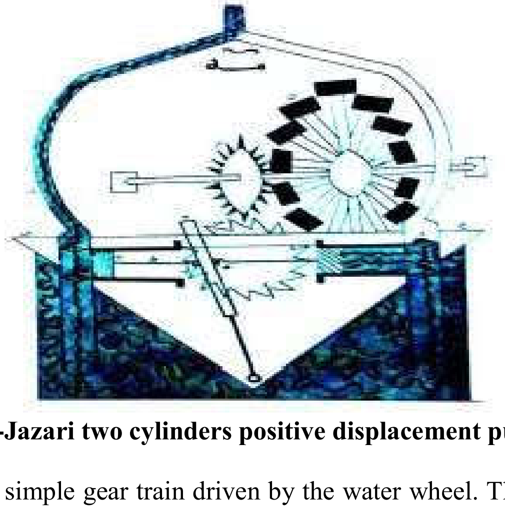

Fig. 1 Al-Jazari two cylinders positive displacement pump [13].

The mechanism crank is a gear in a simple gear train driven by the water wheel. The oscillating lever is a pin (or slider driven) by the crank. The oscillating lever drives to coupler links connected to the two cylinders of the pump.
A line diagram of Al-Jazari mechanism is shown in Fig.2 [10].

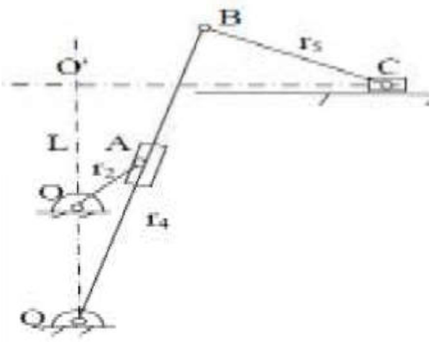

Fig.2 Line diagram of Al-Jazari mechanism [10].

It consists of a rotating crank 2 (replacing the gear in Fig.1), slider at A, oscillating link 4, and coupler 5 and an output slider at C. Therefore, it is a 6-bar mechanism having a unit degree of freedom allowing it to be driven through its crank OA. The output is taken through its second slider at C.

III. MECHANISM ANALYSIS

In order to derive the kinematic functions of the mechanism, it has to be drawn in its two limiting positions as shown in Fig.3 [10].

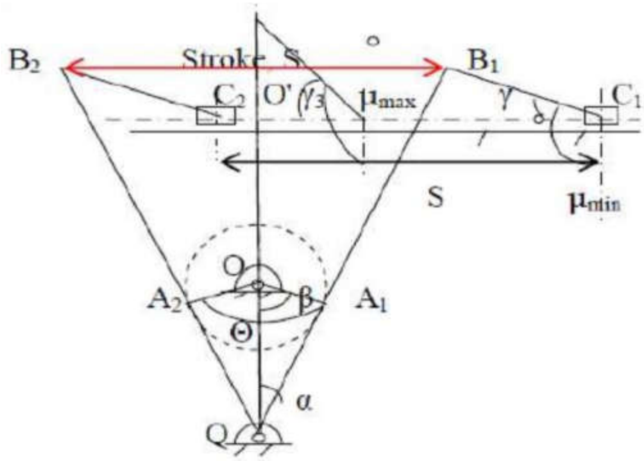

Fig.3 Al-Jazari mechanism in its two extreme positions.

The key performance functions of the mechanism are derived as follows [10]:

- Mechanism dimensions:

r_1 = ground OQ.
r_2 = crank OA
r_4 = oscillating lever QB
r_5 = coupler BC
L = ground OO'

- Normalized dimensions: Normalizing all the mechanism dimensions relative to the crank length r_2, the mechanism has the following four normalized dimensions:

r_{1n} = normalized ground OQ.
r_{4n} = normalized oscillating lever QB
r_{5n} = normalized coupler BC
L_n = normalized ground OO'

- Time ratio, TR:

The time ratio of the mechanism is the ratio between times of the forward stroke to that of the return stroke. In terms of the crank positions in the limiting positions, it is the ratio between the angles 360 – Θ and Θ. That is:

$$TR = (360 - \Theta) / \Theta \quad (1)$$

The crank angle Θ is twice the angle β as shown in Fig.3. That is:

$$\Theta = 2\beta \quad (2)$$

Where:

$$\beta = \cos^{-1}(r_2/r_1) \quad (3)$$

Using the normalized dimensions, Eq.3 becomes:

$$\beta = \cos^{-1}(1/r_{1n}) \quad (4)$$

- Stroke, S:

The stroke S is the distance between the two extreme positions of the output slider at C. Using the geometry of Fig3, the stroke S is given by:

$S = 2r4\sin\alpha$ (5)

Where $\alpha = 90 - \beta$

Using the normalized dimensions, the normalized stroke S_n is given from Eq.5 by:

$S_n = 2r_{4n}\sin\alpha$ (6)

- Minimum transmission angle, TA_{min}:

The minimum transmission angle corresponds to one of the limiting positions of the mechanism is shown in Fig.3. It is the angle between the coupler BC and the vertical through the output slider at C. It is given by:

$TA_{min} = \mu_{min} = \gamma + 90$ degrees (7)

Where: $\gamma = \sin^{-1}\{(r_{4n}/r_{5n}) \cos\alpha - (L_n + r_{1n}) / r_{5n}\}$ - Maximum transmission angle, TA_{max}:

The maximum transmission angle occurs when the oscillating lever is exactly vertical (Fig.3). In this case, TA_{max} is given by:

$TA_{max} = \mu_{max} = \gamma_3 + 90$ degrees (8)

Where: $\gamma_3 = \sin^{-1}\{(r_{4n} - r_{1n} - L_n) / r_{5n}\}$

IV. OPTIMAL MECHANISM SYNTHESIS

The optimal normalized dimensions of Al-Jazari quick return motion mechanism are assigned as follows:

(1) Optimization technique: The MATLAB optimization toolbox is used to maximize the objective functions which is the time ratio of the mechanism given by Eq.1 subjected to constrain of mechanism dimensions and performance functions. The command used is '*fmincon*' [14].

(2) Synthesis variables: The synthesis variables of the mechanism are the following dimensionless variables:

- Normalized first ground: r_{1n}.
- Normalized oscillating lever: r_{3n}.
- Normalized coupler: r_{5n}.
- Normalized second ground: L_n.

(3) Synthesis variables constraints: The normalized mechanism dimensions are subjected to the constraints:

$1.1 \le r_{in} \le 10$ (9)

Where r_{in} stands for r_{1n}, r_{3n}, r_{4n} and L_n of the mechanism.

(4) Functional constraints: The functional constraints are used in the optimization process of the mechanism to adjust its performance as desired by the designer. The functional constraints used in this work are as follows:

- Stroke constraint: To attain a specific desired normalized stroke λ, the following relation exists:

  $S_n \le \lambda$ (10)
- Minimum transmission angle, TA_{min}: As the minimum transmission angle has to be greater than 45 degrees [15], the following functional constraint is required:

  $TA_{min} \ge 45$ degrees (11)
- Maximum transmission angle, TA_{max}: As the maximum transmission angle has to be less than 135 degrees [15], the following functional constraint is required:

  $TA_{max} \le 135$ degrees (12)
- First ground constraint: The first ground length r_1 has to be less than the crank dimension r_2. That is in a normalized form:

  $1 - r_{1n} < 0$ (13)
- Oscillating lever constraint: The oscillating lever length r_{4n} has to be greater than the first ground length r_{1n}. That is:

  $r_{1n} - r_{4n} < 0$ (14)

(5) Optimized mechanism synthesis: The MATLAB command '*fmincon*' is used to maximize the objective function given by Eq.1 subjected to the variables constraints given by Eq.9 and the functional constraints given by Eqs.10 through 14. The results are given in Table 1.

TABLE 1 OPTIMAL SYNTHES OF AL-JAZARI PLANAR QUICK-RETURN MOTION MECHANISM

λ	r_{1n}	r_{4n}	r_{5n}	L_n	TR	S_n	TA_{min} (degrees)	TA_{max} (degrees)
1	4	2	4.3325	1	1.3834	1	45	46.176
1.5	2.6667	2	2.5634	1	1.6480	1.5	45	49.445
2	2	2	2	1	2	2	50.656	60
2.5	1.6	2	2	1	2.5076	2.5	58.709	72.542
3	1.3333	2	2	1	3.3468	3	59.654	80.406
3.5	1.1429	2	2	1	5.2165	3.5	54.034	85.904
4	1.1	2.1165	2	1	6.3111	3.9391	53.221	91.905
4.5	1.1	2.4750	2	1	6.3110	4.5	57.693	100.807
5	1.1	2.7500	2	1	6.3110	5	61.498	108.966
5.5	1.1	3	2	1	6.3110	5.4545	64.843	116.744

(6) The optimal normalized dimensions of Al-Jazari quick return motion mechanism are shown in Fig.4 for a desired normalized stroke from 1 to 5.5.

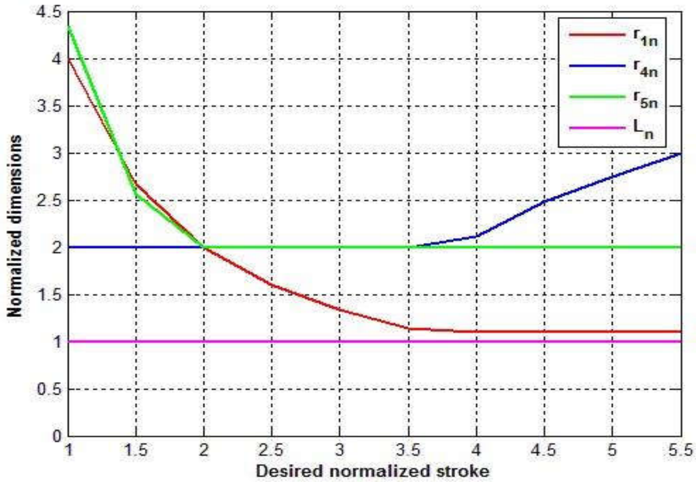

Fig.4 Normalized mechanism dimensions.

(7) The optimal time ratio and normalized stroke are shown in Fig.5 against the desired normalized stroke. Both parameters increase as the desired stroke increses then the time ratio saturates at 6.311.

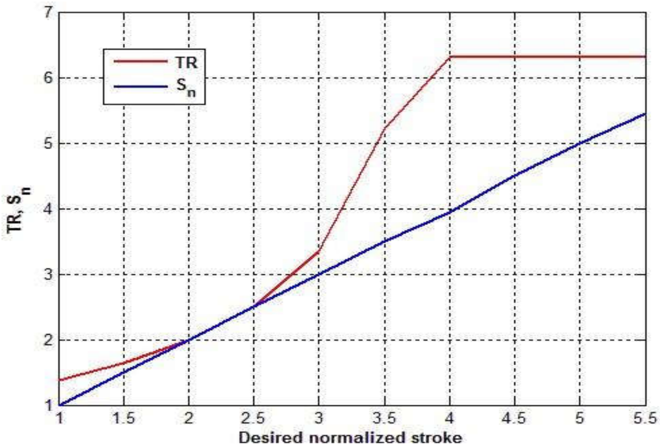

Fig.5 Time ratio and normalized mechanism stroke.

(8) The ptimum minimum and maximum transmission angles are shown in Fig.6 against the desired normalized stroke of the mechanism. The are within the recommended levels of 45 and 135 degrees [15].

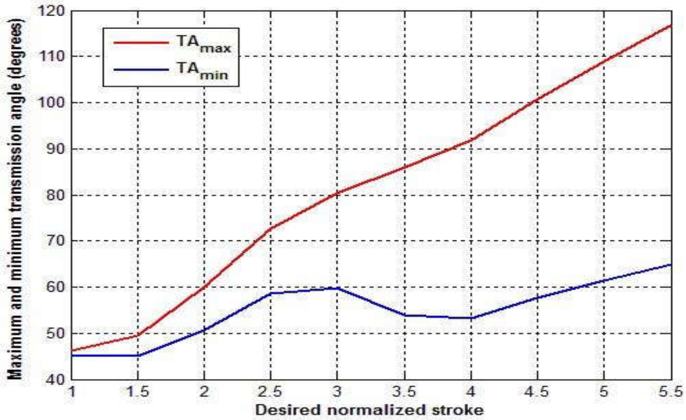

Fig. 6 Optimum minimum and maximum transmission angles.

V. CONCLUSIONS

- Al-Jazari planar quick return motion mechanism was optimally synthesized.
- The mechanism was synthesized using MATLAB optimization toolbox and an objective functions satisfying the requirement of a maximum time ratio.
- Five functional constraints were used to control the kinematical performance of the synthesized mechanism.
- A desired normalized stroke between 1 and 5.5 was used.
- It was possible to reach a maximum time ratio of 6.31.
- It was possible to reach a maximum normalized stroke of 5.4545.
- The synthesis was successful in terms of the mechanism transmission angle. It was within the recommended range of 45 – 135 degrees. The least minimum transmission angle was 45 degrees while the greatest maximum transmission angle was 116.74 degrees.
- The synthesized mechanism belongs to a class of 6-bar mechanisms providing high time ratio up to 6.3.

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